Probabilistic Fatigue Life Analysis of High Density Electronics Packaging

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Abstract

The fatigue life of thin film metal interconnections in high density electronics packaging subjected to thermal cycling has been evaluated using a probabilistic fracture mechanics methodology. This probabilistic methodology includes characterization of thin film stress using an experimentally calibrated finite element model and simulation of flaw growth in the thin metal films using a stochastic crack growth model. The stochastic fatigue life simulation can consider average temperature, thermal cycle amplitude, geometry, material flaw growth behavior, initial flaw size, and uncertainties about the governing parameters and the accuracy of analytical models. The probabilistic approach enables sensitivity analyses to be performed to identify the most important service life and failure risk drivers, so that development effort can be focused more effectively to achieve service life goals

Introduction

The thin film multilayer structures used in multichip module substrates of high density electronic packaging are subject to failure due to thermally induced stress cycling. These thin film structures consist of layers of interconnects and dielectrics deposited and patterned using thin film techniques. The multilayer substrate considered in this paper is a structural system comprised of thin film layers of silicon dioxide dielectric deposited by plasma enhanced chemical vapor deposition, aluminum alloy conductors deposited by sputtering, and anodized aluminum thin film capacitors, all deposited on a silicon wafer.

The application of fracture mechanics to analyze fatigue flaw growth due to thermal cycling in high density electronics packaging using thin films requires detailed knowledge of the stress distribution within the thin film layers. Stress exists in the interconnect structure due to the mismatch in the coefficients of thermal expansion between the thin film layers (thermal stress) and due to the fabrication and deposition processes (intrinsic stress).

Stress and Fatigue Life Analysis

The method used to characterize stress and evaluate aluminum alloy intercon-

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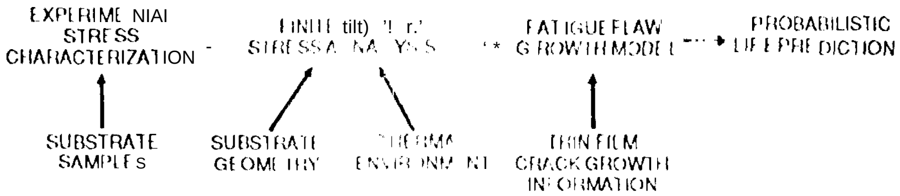

Figure 1. Method Used to Evaluate Interconnect Fatigue Life

nect fatigue life is shown in Figure 1. The experimental stress characterization using the X-ray rocking curve technique was performed on substrate samples removed from the manufacturing process at different stages of completion. The result of the thin film stress measurements were used to calibrate finite element models of the substrate (Kolawa, 1995). Finite element models of features of the aluminum interconnections were constructed with the aid of high magnification photographs to define substrate geometry. The stresses in the aluminum interconnections were used in a fatigue flaw growth model to predict substrate service life under thermal cycling. The fatigue flaw growth analysis was performed probabilistically to enable the identification of information about important governing parameters that is needed to define designs that will survive in extreme thermal environments.

In the flaw growth analysis presented here, *the* fatigue life of aluminum interconnects subjected to thermal cycling is computed probabilistically. The crack growth model used in this analysis can consider cyclic stress due to thermal cycling, mechanical vibration, or other time varying loads. A Monte Carlo simulation procedure is used to calculate life distributions.

The stochastic crack growth rate equation is given by

$$\frac{da}{dN} = \frac{C\,(1-R)^m\,(\lambda_{da}\,\Delta K)^n\,[\,\lambda_{da}\,\Delta K - \lambda_{\Delta K_{TH}}\,\Delta K_{TH}\,]^p}{[\,(1-R)\,K_c - \lambda_{da}\,\Delta K\,]^q} \tag{1}$$

in which da/dN is the crack growth rate, ΔK is the stress intensity factor (SIF) range, ΔK_{TH} is the threshold stress intensity factor range, K_c is the critical stress intensity factor, R is the stress ratio, and C, m, n, p, and q are parameters determined from crack growth data. Uncertainty about the crack growth threshold may be represented in the value of ΔK_{TH}, which is an asymptote to the crack growth rate curve at its lower end. Uncertainty about this asymptote is readily captured by using a scale parameter $\lambda_{\Delta K_{TH}}$. When $\lambda_{\Delta K_{TH}} = 1$, Equation (1) includes the crack growth threshold ΔK_{TH}. When $\lambda_{\Delta K_{TH}} = 0$, there is no crack growth threshold in Equation (1) and all initial flaws will grow. A second parameter, λ_{da}, is used in Equation (1) to represent uncertainty about location of the crack growth curve. The nominal da/dN curve corresponds to $\lambda_{da} = 1$. When $\lambda_{da} > 1$, the crack growth curve is shifted to the left and gives higher values of da/dN for a specified value of Ah. $\lambda_{\Delta K_{TH}}$ and λ_{da} may be characterized by probability distributions, or they may be treated parametrically.

The standard stress intensity factor solution for an edge crack in a finite width plate subject to axial stresses was employed to calculate ΔK for the thin film interconnect strips using the stress as determined by Equation (2). This SIF expression is given as case. TC02 in NASA/JSC, 1986.

The stresses produced in the aluminum interconnects due to thermal cycling are

$$\sigma_{min} = \lambda_{\sigma} (\lambda_{res}\, \sigma_{res} - S_T \Delta T / 2) , \qquad \sigma_{max} = \lambda_{\sigma} (\lambda_{res}\, \sigma_{res} + S_T \Delta T / 2) \qquad (2)$$

where λ_{σ} = finite element stress analysis uncertainty, σ_{res} = residual stress, λ_{res} = residual stress measurement uncertainty, ΔT = temperature change, S_T = thermal stress coefficient from finite element analysis. The parameters σ_{res} and S_T are obtained from finite element modeling of the interconnect structure.

Results

The crack growth model for the thin film Al interconnects is illustrated in Figure 2 for a stress ratio R of 0.75. With the uniform distribution for λ_{da} as shown in Table 1, da/dN for a specified value of ΔK can fall with equal probability at any value between the da/dN curves for $\lambda_{da} = 1$ and $\lambda_{da} = 4$. This characterization of thin film crack growth behavior is based on the fact that fracture toughness of thin sheets decreases as thickness decreases below a critical value above which plane strain fracture just begins to develop. Other information (Private Communication, 1995) about the fracture behavior of thin aluminum foils of thickness reasonably close to that of the interconnects considered here indicates values of fracture toughness K_c of about 10% to 25% of a typical value for larger sections. In addition to reduced fracture toughness Kc, "short crack" behavior is considered to be a reasonable possibility for flaws in very thin aluminum films. There is no crack growth threshold with "short crack" behavior, that is, all flaws grow under stress cycling. The characterization of crack growth behavior shown in Figure 2 captures both of these attributes.

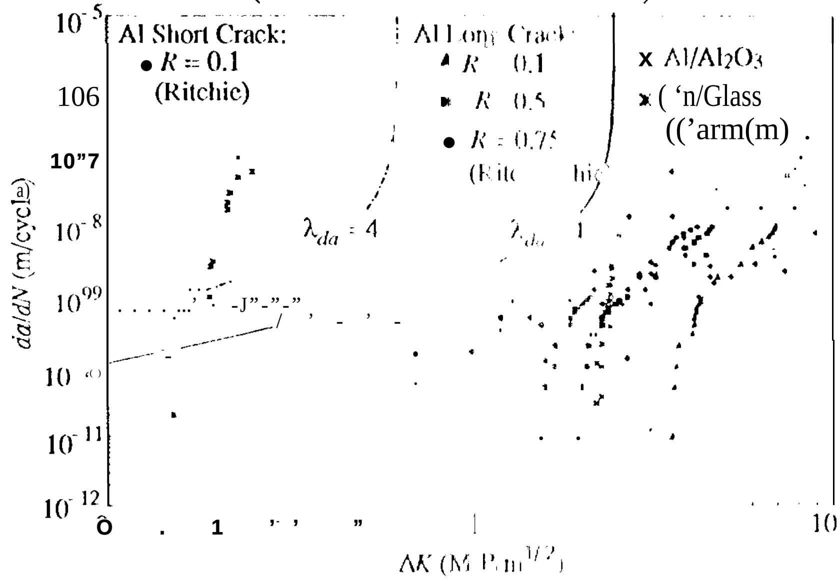

Figure 2. Crack Growth Rate Curves with R = 0.75, m = 0.5, $\lambda_{\Delta K_{TH}}$ = 0, and K_c = 10

The unrelaxed axial stress in the interconnect strip is circa 900 MPa at room temperature, and the relaxed stress is expected to be about 50% of the unrelaxed value. The cumulative life distributions obtained from Monte Carlo simulations (20,000 trials) with σ_{res} at 450 MPa and 900 MPa, initial defect size a_i at 0.1 µm and 0.25 µm, and a thermal cycle amplitude of + 40C to - 10C are shown in Figure 3.

The stress characterization and fatigue life simulation results for the aluminum/silicon dioxide substrate indicate that high residual stresses in the aluminum interconnect lines coupled with stress cycling due to thermal cycles will drive the propagation of small

Table 1. Crack Growth Model Parameters

Location parameter, λ_{da}	.10 to 4.0 (Uniform)
Threshold parameter, $\lambda_{\Delta K_{TH}}$	0. (No threshold)
Residual stress uncertainly, λ_{res}	±5% (Uniform)
Stress analysis uncertainty, λ_{σ}	±35% (Uniform)
SIF uncertainty, λ_{sif}	±10% (Uniform)
Interconnect thickness, µm	2.0 (Fixed)
Initial defect size, µm	0.10 and 0.25 (Fixed)

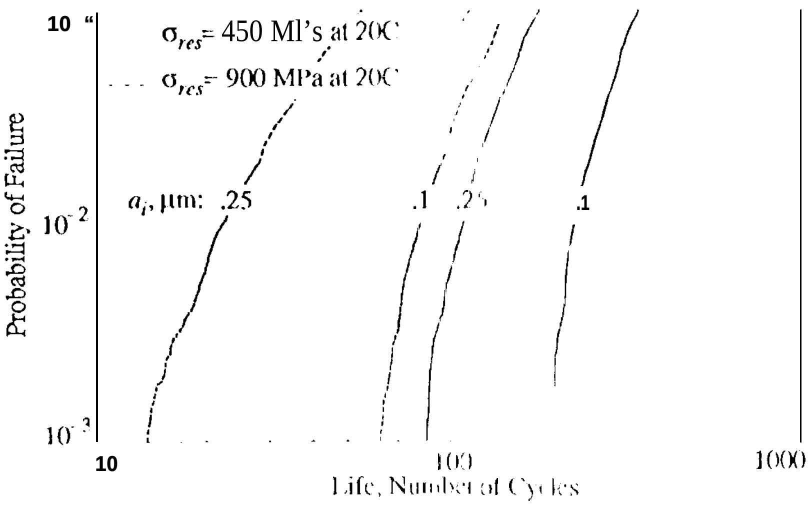

Figure 3. Simulated Failure Distributions of Al Conductors for Thermal Cycling of - 40C to +40C

initial flaws that may result from manufacturing defects or void formation during stress relaxation. Design or manufacturing process changes that may significantly improve thermal cycling fatigue life can be investigated with the probabilistic approach.

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